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# A SIMPLE HYDRIDE MODEL FOR CERIUM EJECTA PARTICLES

JONATHAN D. REGELE, ALAN K. HARRISON, JOHN D. SCHWARZKOPF, WILLIAM T. BUTTLER

Cerium ejecta particles form after a shock wave impacts a cerium plate with a known roughness or prescribed surface perturbation. When these particles are ejected into hydrogen or deuterium gas the material reacts exothermically and raises the temperature of the particle relative to the gas. A simple model is developed, assuming that the particle remains intact and spherical, to capture the heat and mass transfer that occurs during this process. Model performance is evaluated by comparing with cerium ejecta experiments where the particles are ejected into deuterium gas at initial pressures of 4 and 8 atm. Overall, the model is able to capture the approximately 400 K increase in particle temperature above the surrounding gas temperature.

## INTRODUCTION

Ejecta form from Richtmyer-Meshkov (RM) [1, 2] unstable growth of surface perturbations after being impacted by a shock wave. Analytic models exist [3, 4] to describe the evolution of spikes and bubbles that originate from linear surface perturbations (2D unstable sheets) or from single dots (3D spikes). These spikes eventually fragment [5, 6, 7, 8, 9] into individual particles that travel at reasonably well known velocities [4, 10, 11, 12, 13, 14]. The amount of ejecta created is a function of the surface perturbation amplitude and whether the surface is liquid or solid after shock release [15].

The ejecta size/mass and velocity distributions have been studied in both gases and vacuum [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28]. It's known [29] that droplets with sufficiently small Ohnesorge numbers and Weber numbers below a critical value of 11 the droplets are relatively stable and do not breakup much further. In more recent studies [30, 31] of shocked cerium and tin in vacuum, helium and deuterium gases, cerium ejecta particles react with deuterium gas to form cerium dihydride. The exothermic reaction raises the temperature of the particles relative to the gas temperature by up to 400-500 K. In these experiments [30, 31] the tin particles are liquid with an observed mean diameter of 2  $\mu\text{m}$  while the cerium particles are solid with a mean diameter of 13  $\mu\text{m}$ .

A wide range of particle combustion models exist and are summarized in [32, 33, 34] among others. High ash content coal combustion models assume that a layer of ash grows around the outer surface of a reacting coal particle as the char-ash interface moves closer to the particle center. The reaction proceeds as a non-volatile heterogeneous surface reaction. Schwarzkopf *et al.* [35] developed a model for cerium hydriding in deuterium gas that is very similar to the 1-D high ash content model described in [34] where the chemical reaction is controlled by the rate of diffusion through the outer hydride layer.

In this work a similar model is developed that accounts for the spherical nature of the particle along with some other minor differences in model parameters. In section 1, assumptions are made about how to describe the particle and a model is developed for heat and mass transfer. Verification and validation are performed in section 2 and conclusions are made in section 3.

## 1. MATHEMATICAL MODEL

The evolution of cerium ejecta particles is a function of a number of different physical processes, including chemical reactions, heat and mass transfer. In order to develop a simple model of the hydriding process of cerium particles in a deuterium gas, a number of assumptions must be made to simplify the physics involved for the particle:

- the ejecta particles are hydrodynamically stable and spherical
- deuterium must diffuse through a solid layer of cerium dihydride before reaching the unreacted cerium
- deuterium diffuses through the dihydride layer in a quasi-steady manner such that the reaction at the pure cerium surface occurs rapidly
- heat conducts much faster inside the particle relative to the surrounding gas so that the particle temperature can be assumed to be constant.

These assumptions lead to the model illustrated in Fig. 1 where cerium is located in the center of the particle with radius  $a$  and a solid dihydride layer surrounds that region with radius  $b$ . Deuterium must diffuse through the dihydride layer until it reacts rapidly with the cerium. As the cerium reacts, the volume of cerium radius  $a$  retreats as the dihydride layer advances. The particle is at a constant temperature  $T_p$  and the surrounding gas has a concentration  $C_\infty$  or mass fraction  $Y_\infty$  and temperature  $T_\infty$ .

**1.1. Molecular diffusion.** It is assumed that the particles are spherical, hydrodynamically stable and do not breakup any further. The deuterium gas diffuses through a solid layer of cerium dihydride where the gas concentration far away from the particle is  $C_\infty$  or the mass fraction is  $Y_\infty$ . The time unsteady molecular diffusion concentration equation describing this process is expressed

$$(1) \quad \frac{\partial C}{\partial t} = \nabla \cdot \mathcal{D} \nabla C$$

or in terms of mass fraction as

$$(2) \quad \frac{\partial Y}{\partial t} = \nabla \cdot \mathcal{D} \nabla Y$$

where  $C$  is the concentration of deuterium anywhere inside the particle,  $D$  is the diffusion coefficient of deuterium through a solid layer of cerium dihydride, and  $Y$  is the mass fraction. If the particle is hydrodynamically stable, it can be assumed that the particles are at least close to spherical in nature and the laplacian is limited to the radial direction. Additionally, if the diffusion coefficient is assumed to be constant the above equation

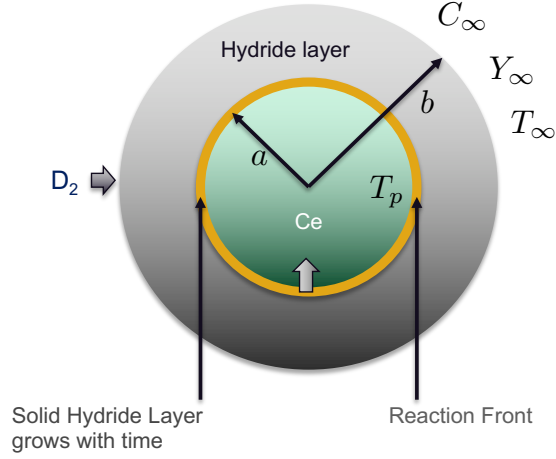


FIGURE 1. Diagram of an ejecta particle with pure cerium surrounded by a layer of cerium dihydride.

becomes

$$(3) \quad \frac{\partial Y}{\partial t} = \mathcal{D} \left( \frac{\partial^2 Y}{\partial r^2} + \frac{2}{r} \frac{\partial Y}{\partial r} \right).$$

Finally, it can be reasonably assumed that the reaction at the cerium surface occurs fast enough that the reaction is diffusion controlled and the concentration of deuterium at the cerium/cerium dihydride interface is negligible ( $Y_s = 0$ ). This is a common assumption in particle combustion models [32, 33, 34] and will be employed here. The resulting differential equation becomes

$$(4) \quad \mathcal{D} \frac{d}{dr} \left( r^2 \frac{dY}{dr} \right) = 0.$$

The solution for the mass fraction as a function of radius is

$$(5) \quad Y(r) = Y_\infty \frac{ab}{a-b} \left( \frac{1}{r} - \frac{1}{a} \right).$$

The mass flux of deuterium reaching the pure cerium surface is evaluated

$$(6) \quad G_{D_2} = -\rho_{D_2} \mathcal{D} \left. \frac{dY}{dr} \right|_{r=a} = \mathcal{D} \frac{\rho_\infty Y_\infty b}{b-a} \frac{1}{a}.$$

Here  $\rho_{D_2}$  is the density of the gas inside the hydride layer,  $\rho_\infty$  is the ambient gas density,  $Y_\infty$  is the ambient gas mass fraction,  $b$  is the particle outer radius and  $a$  is the radius of the cerium/cerium dihydride interface. It's clear that the mass flux  $G \rightarrow \infty$  when  $b = a$  or  $a \rightarrow 0$ . When  $b = a$  the hydride layer has zero thickness, which suggests that the rate limiting step at that point in time would be the chemical kinetics on the initially unreacted cerium surface.

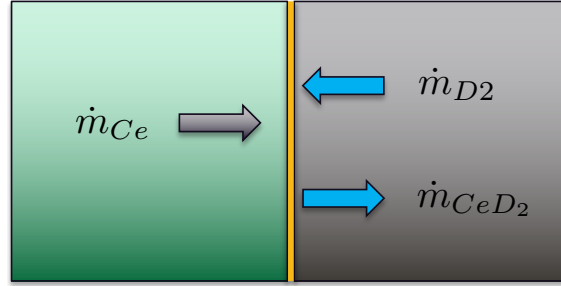
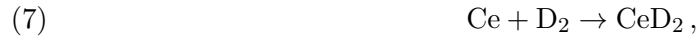


FIGURE 2. Diagram illustrating the movement of cerium, deuterium and cerium dihydride relative to the reaction interface highlighted in yellow. Pure cerium is on the left in green and deuterium diffuses through the solid cerium dihydride before reaching the reaction interface.

**1.2. Reaction model.** Cerium reacts with deuterium to form  $CeD_2$  after which it can continue to produce  $CeD_3$ . The second reaction is slower than the first and doesn't always run to completion so that the final reaction product becomes  $CeD_{2+x}$ , where  $x \in [0, 1]$  [36]. The details of determining the final product composition is beyond the scope of the present work, thus only the first reaction is considered at this time. The reaction can then be written



where one deuterium molecule reacts with each cerium atom. In this instance, the mass stoichiometric coefficient for this reaction is written as a ratio of molecular weights

$$(8) \quad i = \frac{W_{Ce}}{W_{D_2}},$$

which can also be related to the ratio of mass flows and mass fluxes

$$(9) \quad i = \frac{\dot{m}_{Ce}}{\dot{m}_{D_2}} = \frac{G_{Ce}}{G_{D_2}},$$

where the mass flux  $G$  is the mass flow rate per unit area at the cerium/hydride interface. The mass stoichiometric coefficient can be used to rewrite Eq. 7 in terms of mass so that



Now the mass consumption rate of cerium can be directly related to the mass consumption rate of deuterium so that

$$(11) \quad \dot{m}_{Ce} = i \dot{m}_{D_2}.$$

Figure 2 illustrates the flow of the reactant and product species relative to the reaction front highlighted in yellow. Deuterium diffuses through the solid cerium dihydride layer and reacts instantly upon reaching the cerium surface. Mass conservation relative to the

reaction front is written

$$(12) \quad \dot{m}_{CeD_2} = \dot{m}_{Ce} + \dot{m}_{D_2}$$

or in terms of mass flux at the reaction surface

$$(13) \quad G_{CeD_2} = G_{Ce} + G_{D_2}.$$

Cerium dihydride is less dense than pure cerium, which will cause the particle to grow in size as the particle reacts. While this is not difficult to account for in practice, at this point the densities in both regions will be assumed to be constant so that the outer radius of the particle remains constant. In this case, only the inner radius  $a$  changes with time. The mass of cerium inside a sphere is written

$$(14) \quad m_{Ce} = \rho_{Ce} \frac{4}{3} \pi a^3.$$

After differentiation with respect to time, the rate of change of cerium mass becomes

$$(15) \quad \dot{m}_{Ce} = \rho_{Ce} 4\pi a^2 \frac{da}{dt}$$

and the mass flux at the liquid surface can be evaluated by to be

$$(16) \quad G_{Ce} = \frac{\dot{m}_{Ce}}{4\pi a^2} = \rho_{Ce} \frac{da}{dt}.$$

The mass stoichiometric coefficient is used to find the deuterium mass flux

$$(17) \quad G_{D_2} = \frac{\rho_{Ce}}{i} \frac{da}{dt}.$$

The mass flux in Eq. 6 determines the rate at which deuterium diffuses through the cerium dihydride layer and Eq. 17 describes the rate of change of the cerium radius for a given mass flux  $G_{D_2}$ . After equating Eq. 6 and Eq. 17 an ODE describing the rate of change of the cerium radius  $a$  is obtained

$$(18) \quad \frac{da}{dt} = i \frac{\rho_{\infty}}{\rho_{Ce}} \frac{Y_{\infty} \mathcal{D}}{b - a} \frac{b}{a}.$$

The inner radius changes rapidly when  $a$  is initially equal to  $b$  and when  $a \rightarrow 0$ . One-dimensional Cartesian models do not have the  $b/a$  term on the right and thereby do not capture the reaction speedup that occurs for small values of  $a$ . Otherwise, 1-D models are nearly identical to this model for most of the particle reaction period. This equation can be integrated into a parametric expression for  $t = t(a)$  or solved numerically. It should be noted that per MD simulations performed by Daniel Sheppard the diffusivity coefficient increases with temperature.

**1.3. Heat transfer model.** It is common in many particle combustion models [32, 34] to use the lumped capacitance model, which assumes that thermal conduction inside the particle is much faster than convection into the gas so that the particle temperature can be assumed to be uniform. Radiation is assumed to be small relative to convection since the difference in temperature between the two phases is assumed to be small. Convective heat transfer at the surface of the particle and gas is expressed

$$(19) \quad \dot{Q}_c = Nu\pi k_c 2b(T_\infty - T_p),$$

where  $\dot{Q}_c$  is the heat transfer rate,  $Nu$  is the Nusselt number,  $k_c$  is the thermal conductivity of the continuous phase (gas),  $b$  is the outer radius,  $T_\infty$  is the ambient gas temperature and  $T_p$  is the particle temperature. The Ranz-Marshall correlation [37] is a common model for forced convection over spherical particles [38] for Reynolds numbers up to  $5 \times 10^4$  and is written

$$(20) \quad Nu = 2 + 0.6Re_r^{1/2}Pr^{1/3},$$

where  $Re_r$  is the particle Reynolds number using the velocity of the particle relative to the gas and  $Pr$  is the Prandtl number.

**1.4. Energy Conservation.** Energy conservation for a reacting particle with heat transfer can be expressed

$$(21) \quad \dot{E}_p = \dot{Q}_r + \dot{Q}_c,$$

where  $\dot{E}_p$  is the rate of change of internal energy associated with the particle mass,  $\dot{Q}_r$  is the heat release from reaction, and  $\dot{Q}_c$  is the heat transferred to the particle from the gas given in Eq. 19.

The heat release from reaction can be expressed

$$(22) \quad \dot{Q}_r = \dot{m}_{Ce}h_r,$$

where  $h_r$  is the heat of reaction or the amount of energy per unit mass of cerium released during a chemical reaction. The heat of reaction is expressed as the difference of product and reactant enthalpies, i.e.

$$(23) \quad h_r = h_{prod} - h_{reac},$$

where according to Eq. 7  $h_{prod}$  is cerium dihydride's enthalpy of formation  $h_f^0$  and  $h_{reac} = 0$  for both pure cerium and deuterium at STP.

The energy rate of change inside the particle can be written

$$(24) \quad \dot{E}_p = m_p c_p \frac{dT_p}{dt},$$

where  $c_p$  is the specific heat,  $dT_p/dt$  is the particle temperature rate of change, and the particle mass is the sum of all masses inside the particle  $m_p = m_{Ce} + m_{CeD_2} + m_{D_2}$ . Summation of the different terms in Eq. 21 yields

$$(25) \quad \frac{dT_p}{dt} = \frac{Nu}{2} \frac{1}{\pi T} (T_\infty - T_p) + \frac{\dot{m}_{Ce}h_r}{m_p c_p},$$



where the thermal response time [38] is defined

$$(26) \quad \tau_T = \frac{\rho_p c_p (2b)^2}{12k_c},$$

where  $\rho_p$  is the mean particle density  $m_p/V_p$ ,  $c_p$  is the mean particle specific heat and  $k_c$  is the thermal conductivity of the continuous phase (gas).

**1.5. Model summary.** To summarize, the particle hydride model is described with mass and energy conservation equations where mass conservation is expressed as an ordinary differential equation for the cerium particle radius (Eq. 18)

$$(27) \quad \frac{da}{dt} = i \frac{\rho_\infty}{\rho_{Ce}} \frac{Y_\infty \mathcal{D}}{b-a} \frac{b}{a}$$

and energy conservation is written in terms of the particle temperature (Eq. 25)

$$(28) \quad \frac{dT_p}{dt} = \frac{Nu}{2} \frac{1}{\tau_T} (T_\infty - T_p) + \frac{\dot{m}_{Ce} h_r}{m_p c_p}.$$

The cerium mass consumption rate is found by combining Eq. 6 and 9 with  $\dot{m}_{Ce} = 4\pi a^2 G_{Ce}$  to obtain

$$(29) \quad \dot{m}_{Ce} = i4\pi ab \mathcal{D} \frac{\rho_\infty Y_\infty}{b-a}.$$

It is assumed that an appropriate momentum conservation equation will be solved simultaneously with these two conservation laws.

## 2. VERIFICATION AND VALIDATION

The proposed model was coded into python to verify that the model behaves as anticipated and to perform some initial comparisons with experimental data. The model assumes the velocity remains constant and does not change, which limits the applicability of the results to the initial moments after a shock wave has passed. The analysis also focuses on a single particle, which implies that the multiphase mixture it represents is dilute.

A variety of limiting cases were considered to ensure the equations were coded correctly. The first includes verifying that non-reacting particle temperatures asymptote to the surrounding gas temperature on a timescale on the order of the thermal relaxation time  $\tau_T$ . This ensures that the heat transfer model works correctly independent from any reactions. The second test focuses on the diffusion controlled reaction and ensures that a particle with diffusion controlled reactions reacts completely in a time that can be computed analytically to be

$$(30) \quad \tau_r = \frac{1}{6i} \frac{\rho_{Ce}}{\rho_{D_2}} \frac{b^2}{\mathcal{D} Y_\infty}.$$

This solution is obtained by integrating Eq. 27 to obtain  $t(a)$  as a cubic polynomial with  $b$  constant and then evaluating  $t = \tau_r$  with  $a = 0$ . Note that this time is 1/3 the time obtained assuming a planar diffusion model because the spherical coordinate system causes

TABLE 1. Individual input parameters used for the 4 and 8 atm cases.

Initial Gas Pressure [atm]	4	8
Shocked gas temperature $T_\infty$ [K]	720	740
Shocked metal temperature $T_p$ [K]	990	990
Shocked gas density $\rho_\infty$ [kg/m <sup>3</sup> ]	2.3	4.5
Initial particle velocity $u_p$ [mm/ $\mu$ s]	2.39	2.33
Initial gas velocity $u_g$ [mm/ $\mu$ s]	1.91	1.86
Relative velocity $u_r$ [mm/ $\mu$ s]	0.48	0.47
Offset time $t_0$ [ $\mu$ s]	0.85	0.80

Quantity	Symbol	Value
Gas specific heat	$c_p^g$	7.25 J/kg-K
Metal specific heat	$c^m$	37.7 J/kg-K
Particle diameter	$b$	13 $\mu$ m
Particle density	$\rho_p$	6680 kg/m <sup>3</sup>
Gas thermal Conductivity	$k_c$	0.1382 W/m-K
Gas dynamic viscosity	$\mu_c$	1.72E-5 Pa-s
CeD <sub>2</sub> Heat of formation	$h_f^0$	210E+6 J/kmol
Particle atomic mass	$W_p$	140 g/mol
Gas atomic mass	$W_c$	4.0 g/mol
Gas specific heat ratio	$\gamma$	1.4

TABLE 2. Common model parameters used for both the 4 and 8 atm cases.

a  $1/a$  term to appear in Eq. 27, which speeds up the reaction when the particle diameter becomes small.

Preliminary validation tests were performed by modeling the early stages of cerium ejecta experiments where the ejecta particles react with  $D_2$  gas and show a rise in temperature relative the the surrounding gas. Complete details on these experiments and the post-shock conditions calculated using hydrodynamic simulations can be found in [30, 31]. The experiment consists of a high explosive that sends a shock wave through a cerium plate that is machined so that ejecta particles are created with a mean diameter of  $13\mu\text{m}$ . The gas chamber where the particles are ejected into contains deuterium gas at 4 and 8 atm. Table 1 contains the input parameters for each case.

Table 1 also contains the times when the shock emerges from the cerium material into the deuterium gas. This offset time is used to shift the data so that an accurate temporal comparison can be made between the model and experiment. It should be noted that it does take a finite time between when the shock breaks out of the cerium material and hydrodynamically stable ejecta particles are created. This finite time is not currently taken into account for comparisons with the model, since it is unclear what these times are.

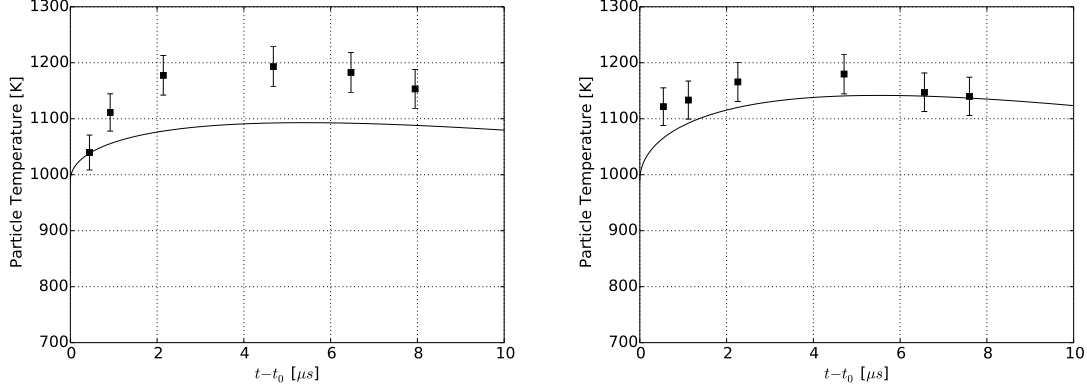


FIGURE 3. Particle temperature as a function of time for 4 (left) and 8 (right) atm cases. The initial gas temperatures are 720 K (left) and 740 K (right).

Table 2 lists the model parameters that are common to both of the 4 and 8 atm cases such as material properties, heat of formation, molecular mass, etc. The diffusivity of  $D_2$  into  $CeD_2$  is calculated using MD simulations for a range of temperatures obtained from Dan Sheppard and an expression for the diffusivity can be expressed as  $D(T_p) = 2.083589E-14 \cdot T_p^{1.941438}$ . Additionally, Sheppard recommends that this diffusivity needs to be multiplied by a factor of 3 to account for the rotational symmetry present. The stoichiometric mass ratio (Eq. 8) is  $i = 35$  and the heat of reaction  $h_r = h_f^0/W_p = 1.5E+6$  J/kg. Most of the metal properties were obtained from [39] and the gas properties were obtained from [40]. The heat of formation of cerium dihydride was obtained from Dan Shepard and is consistent with the range of values documented in [36, 41]. Since the particle mass and diameter are assumed to be constant the mass of the particle is simply  $m_p = \rho_p \pi b^3/6$  where again  $\rho_p = \rho_{Ce}$ .

Figure 3 shows the temperature histories for the 4 and 8 atm cases. The experimental time axis is shifted by the offset time  $t_0$  so that  $t-t_0 = 0$  corresponds to instantaneous ejecta production after the shock emerges from the cerium material. Although we are assuming instantaneous ejecta production for the moment, in reality it will take a finite amount of time for the Richtmyer-Meshkov spike to destabilize and breakup in to hydrodynamically stable ejecta droplets. If this creation time were included it would shift the experimental data further to the left because the model assumes this state from the beginning.

In both cases, the model (solid line) captures roughly the 400-500 K jump in temperature above the gas temperature (720K for 4atm and 740K for 8atm), but the accuracy varies between the two. In the 4 atm case, the model passes through the first temperature data point, but then is consistently lower than the experimental data for the remaining 5 data points by about 100 K. In the 8 atm case the mean difference between the model and

experimental data is less and in general the model comes closer to approximating the experimental data. While the model only passes through the last two data points, the model is only slightly outside the 3% uncertainty range of the second through fourth data points.

It should be noted that at this point only a single particle is considered inside of infinite deuterium gas. In the experiment there is a multiphase mixture of deuterium gas and ejecta particles that transfer momentum, mass and energy in significant quantities between each phase. In order to more accurately estimate the particle temperatures, the temperature rise of the deuterium must be accounted for along with a reduction in the particle relative velocities. However, at this time, the results are compelling enough to believe that with the rough approximations used at this point, these additional corrections will likely lead to more accurate predictions that better capture the transient dynamics of heat release and energy transfer.

### 3. CONCLUSIONS

A simple model is developed to capture the exothermic hydride reaction of cerium material ejected into a deuterium gas. The model assumes the particle remains spherical, is hydrodynamically stable and does not breakup beyond its initial size. The hydride reaction is controlled by diffusion of deuterium through the hydride layer and reacts infinitely fast at the pure cerium metal surface. Despite the simplicity of the model conditions relative to the experiment, the model is able to roughly estimate the 400 K increase in particle temperature above the surrounding gas temperature. It is likely that the transient details will be better represented when additional details are accounted for such as drag forces, finite disperse phase volume fraction, gas phase temperature increase and hydride layer volume expansion.

### REFERENCES

- [1] Robert D. Richtmyer. Taylor instability in shock acceleration of compressible fluids. *Communications on Pure and Applied Mathematics*, 13(2):297–319, 1960.
- [2] E. E. Meshkov. Instability of the interface of two gases accelerated by a shock wave. *Fluid Dynamics*, 4(5):101–104, 1969.
- [3] David Layzer. On The Instability Of Superposed Fluids in a Gravitational Field. *Astrophysical Journal*, 122(1):1–12, 1955.
- [4] Karnig O. Mikaelian. Analytic approach to nonlinear rayleigh-taylor and richtmyer-meshkov instabilities. *Physical Review Letters*, 80(3):508–511, 1998.
- [5] O. Durand and L. Souldard. Large-scale molecular dynamics study of jet breakup and ejecta production from shock-loaded copper with a hybrid method. *Journal of Applied Physics*, 111(4), 2012.
- [6] O. Durand and L. Souldard. Power law and exponential ejecta size distributions from the dynamic fragmentation of shock-loaded Cu and Sn metals under melt conditions. *Journal of Applied Physics*, 114(19), 2013.

- [7] Guy Dimonte, Guillermo Terrones, F. J. Cherne, and P. Ramaprabhu. Ejecta source model based on the nonlinear Richtmyer-Meshkov instability. *Journal of Applied Physics*, 113(2), 2013.
- [8] F. J. Cherne, J. E. Hammerberg, M. J. Andrews, V. Karkhanis, and P. Ramaprabhu. On shock driven jetting of liquid from non-sinusoidal surfaces into a vacuum. *Journal of Applied Physics*, 118(18):185901, 2015.
- [9] O. Durand and L. Souldard. Mass-velocity and size-velocity distributions of ejecta cloud from shock-loaded tin surface using atomistic simulations. *Journal of Applied Physics*, 117(16), 2015.
- [10] Qiang Zhang. Analytical solutions of layzer-type approach to unstable interfacial fluid mixing. *Physical Review Letters*, 81(16):3391–3394, 1998.
- [11] Karnig O. Mikaelian. Limitations and failures of the Layzer model for hydrodynamic instabilities. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 78(1):1–4, 2008.
- [12] Karnig O. Mikaelian. Analytic approach to nonlinear hydrodynamic instabilities driven by time-dependent accelerations. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 81(1):1–16, 2010.
- [13] W. T. Buttler, D. M. Oró, D. L. Preston, Karnig O. Mikaelian, F. J. Cherne, R. S. Hixson, F. G. Mariani, C. Morris, J. B. Stone, G. Terrones, and D. Tupa. Unstable RichtmyerMeshkov growth of solid and liquid metals in vacuum. *J. Fluid Mech.*, 703:60–84, 2012.
- [14] V Karkhanis, P Ramaprabhu, F J Cherne, J E Hammerberg, and M J Andrews. A numerical study of bubble and spike velocities in shock-driven liquid metals. *Journal of Applied Physics*, 025902:0–15, 2018.
- [15] M. B. Zellner, W. Vogan McNeil, G. T. Gray, D. C. Huerta, N. S.P. King, G. E. Neal, S. J. Valentine, J. R. Payton, J. Rubin, G. D. Stevens, W. D. Turley, and W. T. Buttler. Surface preparation methods to enhance dynamic surface property measurements of shocked metal surfaces. *Journal of Applied Physics*, 103(8), 2008.
- [16] J. R. Asay, L. P. Mix, and F. C. Perry. Ejection of material from shocked surfaces. *Applied Physics Letters*, 29:284–287, 1976.
- [17] P. Andriot, P. Chapron, and F. Olive. Ejection of material from shocked surfaces of tin, tantalum and lead-alloys. *AIP Conference Proceedings*, 78:505–509, 1982.
- [18] R Couch, L Shaw, R Barlett, L Steinmetz, W Behrendt, and C Firpo. SURFACE PROPERTIES OF SHOCKED LEAD. *J. Phys. Colloques*, 46(C5):385–393, 1985.
- [19] Roger Cheret, Pierre Chapron, and Philippe Elias. Mass ejection from the free surface of shock-loaded metallic samples. In *In: Gumptra Y.M. (eds) Shock Waves in Condensed Matter.*, pages 651–654. Springer, Boston, MA, Boston, MA, 1986.
- [20] W. S. Vogan, W. W. Anderson, M. Grover, J. E. Hammerberg, N. S.P. King, S. K. Lamoreaux, G. MacRum, K. B. Morley, P. A. Rigg, G. D. Stevens, W. D. Turley, L. R. Veaser, and W. T. Buttler. Piezoelectric characterization of ejecta from shocked tin surfaces. *Journal of Applied Physics*, 98(113508), 2005.
- [21] M. B. Zellner, M. Grover, J. E. Hammerberg, R. S. Hixson, A. J. Iverson, G. S. MacRum, K. B. Morley, A. W. Obst, R. T. Olson, J. R. Payton, P. A. Rigg, N. Routley,

- G. D. Stevens, W. D. Turley, L. Veaser, and W. T. Buttler. Effects of shock-breakout pressure on ejection of micron-scale material from shocked tin surfaces. *Journal of Applied Physics*, 102(013522), 2007.
- [22] M. B. Zellner, W. Vogan McNeil, J. E. Hammerberg, R. S. Hixson, A. W. Obst, R. T. Olson, J. R. Payton, P. A. Rigg, N. Routley, G. D. Stevens, W. D. Turley, L. Veaser, and W. T. Buttler. Probing the underlying physics of ejecta production from shocked Sn samples. *Journal of Applied Physics*, 103(123502), 2008.
- [23] Michael B. Zellner, Guy Dimonte, Timothy C. Germann, James E. Hammerberg, Paulo A. Rigg, Gerald D. Stevens, William D. Turley, and William T. Buttler. Influence of shockwave profile on ejecta. *AIP Conference Proceedings*, 1195:1047–1050, 2009.
- [24] Yongtao Chen, Haibo Hu, Tiegang Tang, Guowu Ren, Qingzhong Li, Rongbo Wang, and William T. Buttler. Experimental study of ejecta from shock melted lead. *Journal of Applied Physics*, 111(053509), 2012.
- [25] S. K. Monfared, D. M. Oró, M. Grover, J. E. Hammerberg, B. M. Lalone, C. L. Pack, M. M. Schauer, G. D. Stevens, J. B. Stone, W. D. Turley, and W. T. Buttler. Experimental observations on the links between surface perturbation parameters and shock-induced mass ejection. *Journal of Applied Physics*, 116(063504), 2014.
- [26] D. S. Sorenson, R. W. Minich, J. L. Romero, T. W. Tunnell, and R. M. Malone. Ejecta particle size distributions for shock loaded Sn and Al metals. *Journal of Applied Physics*, 92:5830–5836, 2002.
- [27] V. A. Ogorodnikov, A. L. Mikhlov, V. V. Burtsev, S. A. Lobastov, S. V. Erunov, A. V. Romanov, A. V. Rudnev, E. V. Kulakov, Yu B. Bazarov, V. V. Glushikhin, I. A. Kalashnik, V. A. Tsyganov, and B. I. Tkachenko. Detecting the ejection of particles from the free surface of a shock-loaded sample. *Journal of Experimental and Theoretical Physics*, 109(3):530–535, 2009.
- [28] S. K. Monfared, W. T. Buttler, D. K. Frayer, M. Grover, B. M. Lalone, G. D. Stevens, J. B. Stone, W. D. Turley, and M. M. Schauer. Ejected particle size measurement using Mie scattering in high explosive driven shockwave experiments. *Journal of Applied Physics*, 117(223105), 2015.
- [29] D. R. Guildenbecher, C. López-Rivera, and P. E. Sojka. Secondary atomization. *Experiments in Fluids*, 46:371–402, 2009.
- [30] W. T. Buttler, S. K. Lamoreaux, R. K. Schulze, J. D. Schwarzkopf, J. C. Cooley, M. Grover, J. E. Hammerberg, B. M. La Lone, A. Llobet, R. Manzanares, J. I. Martinez, D. W. Schmidt, D. G. Sheppard, G. D. Stevens, W. D. Turley, and L. R. Veaser. Ejecta Transport, Breakup and Conversion. *Journal of Dynamic Behavior of Materials*, 3(2):334–345, 2017.
- [31] William T. Buttler. ( U ) Ejecta transport breakup and conversion : DR Progress report. Technical report, LA-UR-19-21158, 2019.
- [32] Stephen R. Turns. *An introduction to combustion : concepts and applications*. McGraw-Hill, New York, 2nd edition, 2006.
- [33] Thierry Poinso and Denis Veynante. *Theoretical and Numerical Combustion*. R. T. Edwards, Philadelphia, 2nd edition, 2005.

- [34] Irvin Glassman. *Combustion*. Academic Press, San Diego, CA, 3rd edition, 1996.
- [35] J D Schwarzkopf, D G Sheppard, J E Hammerberg, M M Schauer, W T Buttler, and R K Schulze. Modeling of Ce ejecta in He (non-reactive) and D2 (reactive) gases. In *21st Biennial Conference of the APS Topical Group on Shock Compression of Condensed Matter (SHOCK2019)*, Portland, OR, 2019.
- [36] William L. Korst and James C. Warf. Rare Earth-Hydrogen Systems. I. Structural and Thermodynamic Properties. *Inorganic Chemistry*, 5(10):1719–1726, 1966.
- [37] W E Ranz and W R Marshall. Evaporation from Drops. *Chemical Engineering Progress*, 48(3):141–146, 1952.
- [38] C T Crowe, J D Schwarzkopf, M Sommerfeld, and Y Tsuji. *Multiphase Flows with Droplets and Particles*. CRC Press, 2 edition, 2012.
- [39] Cerium - Ce, <https://www.lenntech.com/periodic/elements/ce.htm>, 2019.
- [40] Deuterium - Gas Encyclopdeia, <https://encyclopedia.airliquide.com/deuterium>, 2019.
- [41] A. S. Chernikov, V. I. Savin, V. N. Fadeev, N. A. Landin, and L. A. Izhvanov. Thermodynamic and physical properties of yttrium and some rare earth hydrides. *Journal of The Less-Common Metals*, 130:441–452, 1987.